Renewable and Sustainable Energy Reviews 15 (2011) 2810–2825

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Exergetic and exergoeconomic aspects of wind energy systems in achieving sustainable development

Arif Hepbasli*, Zeyad Alsuhaibani

Department of Mechanical Engineering, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia

ARTICLE INFO

Article history:
Received 14 December 2010
Accepted 20 February 2011

Keywords:
Energy analysis
Exergy analysis
Exergoecomomic analysis
Energy efficiency
Exergy efficiency
Lowex
Wind energy system
Wind energy
Wind exergy map
Renewable energy
Sustainability

ABSTRACT

Utilization of renewable energy resources appears to be one of the most efficient and effective ways in achieving sustainable development, that is now widely seen as important to worldwide public opinion. Among renewable energy sources, wind energy, which is a free, clean, and renewable source of energy, which will never run out, plays a big role. In this context, a number of studies on the efficient utilization of wind energy resources have been conducted by various investigators to attain sustainable development. Most of them have included their energetic aspects, while the number of studies conducted on their exergetic and exergoeconomic directions is relatively very low.

In recent years, exergy, which is a means to sustainable development, has become a very effective tool in evaluating system effectiveness and in designing the system to maximize energy savings. Exergoeconomic analysis, which is a combination of exergy and economics, is also nowadays considered a powerful tool to study and optimize various types of energy-related systems.

The present study comprehensively reviews the studies conducted on exergetic and exergoeconomic analysis and assessment of wind energy systems and suggests possible future works to be performed for the first time to the best of the authors' knowledge. In this regard, an introductory information is given first. Next, wind energy systems exergetically and exergoeconomically analyzed and evaluated are presented and shortly described. The previously conducted studies on these systems are then reviewed and classified in the tabulated forms. Finally, the conclusions drawn are presented. It is expected that this comprehensive contribution will be very beneficial to everyone involved or interested in the energetic, exergetic and exergoeconomic design, analysis and performance evaluation of wind energy systems.

Contents

Abbreviations: EXCEM, exergy cost energy and mass; VAWT, vertical axis wind turbine; WP, wind power; WPRO, wind-powered seawater reverse osmosis system.

* Corresponding author. Tel.: +966 14676677; fax: +966 14672636.
E-mail addresses: ahepbasli.c@ksu.edu.sa, arifhepbasli@gmail.com (A. Hepbasli), zeyads@ksu.edu.sa (Z. Alsuhaibani).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2011.02.031

Nomenclature

AEP	annual energy production (kJ/year or MWh/year)
A	area (m^2)
C	specific heat (kJ/kgK), coefficient
CF	capacity factor
Cosψ	power factor
E	energy amount (kJ)
$\dot{E}$	energy rate (kW)
ex	specific exergy (kJ/kg)
Ex	exergy amount (kJ)
$\dot{\mathrm{E}}\mathrm{x}$	exergy rate (kW)
f	exergetic factor
$\dot{F}$	exergy rate of fuel (kW)
g	gravitational acceleration (m^2/s)
h	specific enthalpy (kJ/kg)
H	height (m), higher heating (gross calorific) value (kJ/kg)
I	phase current (A)
$\dot{I}$	rate of irreversibility, rate of exergy consumption (kW)
$\mathrm{I}\dot{\mathrm{P}}$	rate of improvement potential (kW)
K	capital cost (US$)
$\dot{L}$	thermodynamic loss rate (kW)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa), capacity (MW)
$\dot{P}$	exergy rate of the product (kW)
$\dot{Q}$	heat transfer rate (kW)
Q	heat transfer amount (kJ)
R	gas constant (kJ/kgK), maximum rotor radius (m), ratio (−)
$\dot{R}$	ratio of thermodynamic loss rate-to-capital cost (kW/US$)
s	specific entropy (kJ/kgK)
$\dot{S}$	entropy rate (kW/K)
SExI	specific exergy index
SI	sustainability index
t	time (s)
T	temperature (°C or K)
V	volume (km^3), velocity (m/s), voltage (V)
W	work (kJ)
$\dot{W}$	rate of work (or power) (kW)
z	elevation (m)

Greek letters

η	energy (first law) efficiency (dimensionless)
ψ	flow (specific) exergy (kJ/kg)
Δ	interval
ρ	density (kg/m^3)
β	proportionality constant (or quality factor or exergy coefficient)
δ	fuel depletion rate
ε	exergy (second law) efficiency
ξ	productivity lack
χ	relative irreversibility
μ	Hellmann coefficient

Indices

a	air, actual
act	actual
at	atmospheric
b	bearing
CV	control volume
dest	destroyed, destruction
E	energetic
e	electrical
en	energetic
ex	exergy, exergetic
f	functional, fluid
g	generator
gen	generation
i	successive number of elements, inside surrounding
in	input
inst	installed
k	location
KN	kinetic
LL	phase to phase voltage
m	mechanical
out	output
p	power
per	perfect
PH	physical
q	heat
ref	reference
Ren	renewability
s	stream
T	total
u	universal
u	useful
v	vapor
W	work
WF	wind farm
windch	wind chill
WT	wind turbine
0	dead (reference) state
1	initial state
2	final state

1. Introduction

The European Union (EU) from the beginning of 2007 has focused its emphasis on developing a new policy that puts energy back at the heart of EU action [1]. European energy strategy and policy are strongly driven by the twin objectives of sustainability (including environmental aspects) and security of supply. Implementation of new energy technologies are of big importance for satisfying these objectives, such as renewable energy systems at the supply side and improved energy end-use efficiency at the demand side [1,2].

Research into future alternatives has been and still being conducted to aim at solving the complex problems of this recent time, e.g., rising energy requirements of a rapidly and constantly growing world population and global environmental pollution. Therefore, options for a long-term and environmentally friendly energy supply have to be developed leading to the utilization of renewable sources (water, sun, wind, biomass, geothermal, hydrogen) and fuel cells. Renewables could shield a nation from the negative effect in the energy supply, price and related environment concerns [3].

Achieving sustainable development is a target that is now widely seen as important to worldwide public opinion. In this regard, the utilization of renewable energy resources appears to be one of the most efficient and effective ways in achieving this target [4].

Among renewable energy sources, wind energy, which is a free, clean and renewable source of energy, which will never run out. Hence, electricity generation from the wind is considered economical as well as environmentally friendly. The wind energy industry is growing at a rapid pace and is set to expand globally as a source of cleaner and more sustainable power generation [5]. In other words, wind power is the world's fastest growing electricity generation technology.

In 2009, a total of 38,103 MW of new wind installations was recorded, with the total installed global wind power capacity now standing at 160 GW. This represents an increase in cumulative installations of 31%, and a 35% rise in the rate of annual installations. This was the fifth year in a row with record installations, albeit a slightly lower rate compared with the 42% achieved in 2008. The global pattern, however, has shifted significantly, with both the US and particularly China seeing very strong growth in 2009. Europe maintained a steadier rate, but with 28% of the market it now indicates a lower share of the 2009 global installations than either South and East Asia, which had 39% of the overall market, and the Americas, which had 30%. Nonetheless, the European cumulative total is still nearly 48% of global capacity [6].

In attaining sustainable development, increasing the energy efficiencies of processes utilizing sustainable energy resources plays an important role. There is a link between exergy and sustainable development. A sustainable energy system may be regarded as a cost-efficient, reliable, and environmentally friendly energy system that effectively utilizes local resources and networks [7]. In recent years, exergy, which is a means to sustainable development, has become a very effective tool in evaluating system effectiveness and in designing the system to maximize energy savings [8].

Dincer [9] reported the linkages between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making and exergy in detail. He provided the following key points to highlight the importance of the exergy and its essential utilization in numerous ways: (a) it is a primary tool in best addressing the impact of energy resource utilization on the environment. (b) It is an effective method using the conservation of mass and conservation of energy principles together with the second-law of thermodynamics for the design and analysis of energy systems. (c) It is a suitable technique for furthering the goal of more efficient energy-resource use, for it enables the locations, types, and true magnitudes of wastes and losses to be determined. (d) It is an efficient technique revealing whether or not and by how much it is possible to design more efficient energy systems by reducing the inefficiencies in existing systems. (e) It is a key component in obtaining a sustainable development.

Exergy is a measure of the maximum useful work that can be done by a system interacting with an environment that is at a constant pressure P_0 and a temperature T_0. The convertible energy of a system is proportional to the difference between an energy source and its surroundings. Therefore, energy and exergy do not stand for the same meaning [10]. Exergy can also identify better than energy the environmental benefits and economics of energy technologies. The results suggest that exergy should be utilized by engineers and scientists, as well as decision and policy makers, involved in green energy and technologies in tandem with other objectives and constraints [11].

An exergy analysis (or second law analysis) has proven to be a powerful tool in the design, simulation and assessment of various energy-related systems. Exergy analysis method is employed to detect and to evaluate quantitatively the causes of the thermodynamic imperfection of the process under consideration. It can, therefore, indicate the possibilities of thermodynamic improvement of the process under consideration, but only an economic analysis can decide the expediency of a possible improvement. In this [12,13].

The exergoeconomic analysis is a method that combines exergy analysis with economic analysis. The method provides a technique to evaluate the cost of inefficiencies or the costs of individual process streams, including intermediate and final products [14], as determined for a combined heat and power system [15]. Exergoeconomics is currently a powerful tool to study and optimize an energy system. The application field is the evaluation of utility cost as products or supplies of production plants, the energy cost between process and operations of an energy converter. These costs are applicable in feasibility studies, in investment decisions, on comparing alternative techniques and operating conditions, in a cost-effective section of equipment during an installation, an exchange or expansion of an energy system [16].

The present study comprehensively reviews various studies conducted on wind energy systems from the exergetic and exergoeconomic points of view. In this regard, the structure of the paper is organized as follows: The first section includes the introduction; Section 2 deals with the general energetic, exergetic and exergoeconomic relations used in the analysis and assessment of wind energy systems, while wind energy-related relations including exergetic aspects are given in Section 3; the previously conducted studies are reviewed and classified in Section 4; Section 5 covers the possible future works to be conducted; and the last section concludes.

2. General energetic, exergetic and exergoeconomic relations for wind energy systems

2.1. Mass balance relations

A general expression for the conservation of mass of a control volume is given by [17]

$$\frac{dm_{CV}}{dt} = \sum_{in} \dot{m}_{in} - \sum_{out} \dot{m}_{out} \tag{1a}$$

where the left side represents the time rate of change of mass contained within the control volume, and the subscripts 'in' and 'out' stand for inlet and outlet states, respectively.

In steady-state, $\mathrm{d}m_{CV}/\mathrm{d}t = 0$. Therefore Eq. (1a) reduces to

$$\sum_{in} \dot{m}_{in} = \sum_{out} \dot{m}_{out} \tag{1b}$$

2.2. General energetic relations

The energy balance on a rate basis for a control volume with multiple inlets and outlets is written as [17]

$$\frac{\mathrm{d}E_{CV}}{\mathrm{d}t} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum_{in} \dot{m}_{in}\left(h + \frac{V^2}{2} + gz\right)_{in} - \sum_{out} \dot{m}_{out}\left(h + \frac{V^2}{2} + gz\right)_{out} \tag{2a}$$

where $\mathrm{d}E_{CV}/\mathrm{d}t$ is the time rate of change of energy, $\dot{Q}_{CV}$ is the heat transfer rate over the boundary of the control volume, $\dot{W}_{CV}$ includes work effects, such as those associated with rotating shafts, displacement of the boundary, and electrical effects, h is the specific enthalpy, V is the velocity and z is the elevation.

In steady-state, $\mathrm{d}E_{CV}/\mathrm{d}t = 0$. Therefore Eq. (2a) reduces to

$$\dot{Q}_{CV} - \dot{W}_{CV} = \sum_{out} \dot{m}_{out}\left(h + \frac{V^2}{2} + gz\right)_{out} - \sum_{in} \dot{m}_{in}\left(h + \frac{V^2}{2} + gz\right)_{in} \tag{2b}$$

2.3. General exergetic relations

Exergy is always evaluated with respect to a reference environment (i.e., dead state). When a system is in equilibrium with the environment, the state of the system is called the dead state due to the fact that the exergy is zero. At the dead state, the conditions of mechanical, thermal, and chemical equilibrium between the system and the environment are satisfied: the pressure, temperature, and chemical potentials of the system equal those of the environment, respectively. In addition, the system has no motion or elevation relative to coordinates in the environment. Under these conditions, there is neither possibility of a spontaneous change within the system or the environment nor an interaction between them. The value of exergy is zero. Another type of equilibrium between the system and environment can be identified. This is a restricted form of equilibrium, where only the conditions of mechanical and thermal equilibrium (thermo-mechanical equilibrium) must be satisfied. Such state is called the restricted dead state. At the restricted dead state, the fixed quantity of matter under consideration is imagined to be sealed in an envelope impervious to mass flow, at zero velocity and elevation relative to coordinates in the environment, and at the temperature T_0 and pressure P_0 taken often as 25 °C and 1 atm [18].

In steady-state, exergy balance equation may be written as follows:

$$0 = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \dot{W}_{CV} + \sum \dot{m}_{in}\mathrm{ex}_{in} - \sum \dot{m}_{out}\mathrm{ex}_{out} - \dot{E}\mathrm{x}_{dest} \tag{3a}$$

Expressed in terms of the time rates of exergy transfer and destruction, Eq. (3a) takes the form [17]

$$0 = \sum_j \dot{E}\mathrm{x}_{q,j} - \dot{W}_{CV} + \sum \dot{E}\mathrm{x}_{in} - \sum \dot{E}\mathrm{x}_{out} - \dot{E}\mathrm{x}_{dest} \tag{3b}$$

where $\dot{E}\mathrm{x}_{in}$ and $\dot{E}\mathrm{x}_{out}$ are exergy transfer rates at inlets and outlets, respectively, and $\dot{E}\mathrm{x}_{q,j}$ is given by Eq. (3c).

The term $\dot{Q}_j$ represents the heat transfer rate at the location on the boundary of the control volume where the instantaneous temperature is T_j and the associated exergy transfer rate is given by

$$\dot{E}\mathrm{x}_{q,j} = \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j \tag{3c}$$

As the control volume energy rate balance, $\dot{W}_{CV}$ indicates the energy transfer rate by work other than flow work. The associated exergy transfer rate is given by

$$\dot{E}\mathrm{x}_W = \dot{W}_{CV} - P_0\frac{\mathrm{d}V_{CV}}{\mathrm{d}t} \tag{3d}$$

The term $\dot{W}$ indicates energy transfer rate by work, and the associated exergy transfer is given by $\dot{W} - P_0(\mathrm{d}V/\mathrm{d}t)$ where $\mathrm{d}V/\mathrm{d}t$ is the time rate of change of system volume. $\dot{E}\mathrm{x}_{dest}$ accounts for exergy destruction rate due to irreversibilities within the system and is related to entropy generation rate by $\dot{I} = \dot{E}\mathrm{x}_{dest} = T_0\dot{S}_{gen}$.

The general exergy balance can also be written as follows [7]:

$$\sum \dot{E}\mathrm{x}_{in} - \sum \dot{E}\mathrm{x}_{out} = \sum \dot{E}\mathrm{x}_{dest} \tag{4a}$$

$$\dot{E}\mathrm{x}_{heat} - \dot{E}\mathrm{x}_{work} + \dot{E}\mathrm{x}_{mass,in} - \dot{E}\mathrm{x}_{mass,out} = \dot{E}\mathrm{x}_{dest} \tag{4b}$$

with

$$\dot{E}\mathrm{x}_{heat} = \sum \left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k \tag{4c}$$

$$\dot{E}\mathrm{x}_{work} = \dot{W} \tag{4d}$$

$$\dot{E}\mathrm{x}_{mass,in} = \sum \dot{m}_{out}\psi_{out} \tag{4e}$$

$$\dot{E}\mathrm{x}_{mass,out} = \sum \dot{m}_{out}\psi_{out} \tag{4f}$$

$$\psi = \mathrm{ex} = (h - h_0) - T_0(s - s_0) \tag{4g}$$

where $\dot{Q}_k$ is the heat transfer rate through the boundary at temperature T_k at location k and $\dot{W}$ is the work rate.

In wind energy systems, determination of the total flow exergy of air is very essential and it may be calculated from [19]

$$\begin{aligned}\psi_{a,t} = {} & (C_{p,a} + \omega C_{p,v})T_0\left[\left(\frac{T}{T_0}\right) - 1 - \ln\left(\frac{T}{T_0}\right)\right] \\ & + (1 + 1.6078\omega)R_aT_0 \ln\left(\frac{P}{P_0}\right) \\ & + R_aT_0\left\{(1 + 1.6078\omega)\ln\left[\frac{1 + 1.6078\omega_0}{1 + 1.6078\omega}\right] \right. \\ & \left. + 1.6078\omega \ln\left(\frac{\omega}{\omega_0}\right)\right\}\end{aligned} \tag{5a}$$

where the specific humidity ratio is

$$\omega = \dot{m}_v/\dot{m}_a \tag{5b}$$

or assuming air to be a perfect gas, the specific physical exergy of air is calculated by the following relation [20]

$$\psi_{a,per} = C_{p,a}\left(T - T_0 - T_0\ln\left(\frac{T}{T_0}\right)\right) + R_aT_0\ln\left(\frac{P}{P_0}\right) \tag{5c}$$

The flow exergy rates of the air may be calculated using one of the following relations:

$$\dot{\mathrm{E}}\mathrm{x}_{a,t} = \dot{m}\psi_{a,t} \quad (6)$$

$$\dot{E}x_{a,\mathrm{per}} = \dot{m}\psi_{a,\mathrm{per}} \quad (7)$$

2.4. Some exergetic parameter

Thermodynamics analysis of energy-related systems may also be performed using the following parameters [18]:

- Fuel depletion ratio:

$$\delta_i = \frac{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{dest},}}{\dot{F}_{\mathrm{T}}} \quad (8)$$

- Relative irreversibility (exergy destruction):

$$\chi_i = \frac{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{dest},}}{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{dest},}} \quad (9)$$

- Productivity lack:

$$\xi_i = \frac{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{dest},}}{\dot{P}_{\mathrm{T}}} \quad (10)$$

- Exergetic factor:

$$f_i = \frac{\dot{F}_i}{\dot{F}_{\mathrm{T}}} \quad (11)$$

Some other parameters, namely energetic renewability ratio, exergetic renewability ratio, energetic reinjection ratio, and exergetic reinjection ratio for geothermal systems have been developed by Coskun et al. [21] as follows:

Energetic renewability ratio is defined as the ratio of useful renewable energy obtained from the system to the total energy input (all renewable and non-renewable together) to the system and given by

$$R_{\mathrm{Ren},E} = \frac{\dot{E}_{\mathrm{useful}}}{\dot{E}_{\mathrm{T}}} \quad (12)$$

Exergetic renewability ratio is defined as the ratio of useful renewable exergy obtained from the system to the total exergy input (all renewable and non-renewable together) to the system and calculated using

$$R_{\mathrm{Ren,Ex}} = \frac{\dot{E}_{\mathrm{useful}}}{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{T}}} \quad (13)$$

2.5. Exergetic improvement potential rate

Van Gool [22] has also proposed that maximum improvement in the exergy efficiency for a process or system is obviously achieved when the exergy loss or irreversibility ($\dot{\mathrm{E}}\mathrm{x}_{\mathrm{in}} - \dot{\mathrm{E}}\mathrm{x}_{\mathrm{out}}$) is minimized. Consequently, he suggested that it is useful to employ the concept of an exergetic "*improvement potential*" when analyzing different processes or sectors of the economy. This improvement potential in the rate form, denoted $\mathrm{I}\dot{\mathrm{P}}$, is given by

$$\mathrm{I}\dot{\mathrm{P}} = (1-\varepsilon)(\dot{\mathrm{E}}\mathrm{x}_{\mathrm{in}} - \dot{\mathrm{E}}\mathrm{x}_{\mathrm{out}}) \quad (14)$$

2.6. Energy and exergy efficiency relations

Basically, the energy efficiency of the system can be defined as the ratio of total energy output to total energy input

$$\eta = \frac{\dot{E}_{\mathrm{output}}}{\dot{E}_{\mathrm{input}}} \quad (15)$$

where in most cases "*output*" refers to "*useful*" one [7].

Exergy efficiency may be defined in various ways, namely universal exergy efficiency (ε_{U}) and functional exergy efficiency (ε_{F}), as given below, respectively [7]:

$$\varepsilon_{\mathrm{U}} = \frac{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{out}}}{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{in}}} \quad (16)$$

where "out" refers to total exergy output and "in" refers to total exergy input.

$$\varepsilon_{\mathrm{F}} = \frac{\text{exergetic product}}{\text{exergetic fuel}} = \frac{\dot{P}}{\dot{F}} \quad (17)$$

2.7. General exergoeconomic relations

In recent years, various exergy-based economic analysis methodologies (e.g., exergoeconomics, thermoeconomics, second-law costing) have been applied by many investigators to numerous energy systems (e.g., [23–27]). As far as exergoeconomic assessments of wind energy systems are concerned, up to date there are very limited studies, which have been reported in the open literature. One of these studies included exergy, cost, energy and mass (EXCEM) method.

This EXCEM method proposed by Rosen and Scott [28] could be useful to investigators in engineering and other disciplines. The methodology provides a comprehensive assessment by accounting for the EXCEM quantities, as explained below [28,29].

The energy loss rate for a system is denoted as (loss rate based on energy), as given below:

$$\dot{L}_{\mathrm{en}} = \text{waste energy output rate} \quad (18)$$

The loss rate based on exergy, $\dot{L}_{\mathrm{ex}}$, is defined as;

$$\dot{L}_{\mathrm{ex}} = \text{exergy consumption rate} + \text{waste exergy output rate} \quad (19)$$

The capital cost (K) is simply that part of the cost generation attributable to the cost of equipment. The principal reason that capital costs are used here is that the use of the cost generation term increases significantly the complexity of the analysis, since numerous other economic details (interest rates, component lifetimes, salvage values, etc.) must be fully known. There are two main justifications for this simplification:

- Capital costs are often the most significant component of the total cost generation. Hence, the consideration of only capital costs closely approximates the results when cost generation is considered.
- Cost generation components other than capital costs often are proportional to capital costs. Hence, the trends identified in the present work will likely be in qualitative agreement with those identified when the entire cost generation term is considered.

For a thermal system operating normally in a continuous steady-state steady-flow process mode, the energy and exergy loss rates can be obtained through the following equations:

$$\dot{L}_{\mathrm{en}} = \sum_{\mathrm{inputs}} \dot{E} - \sum_{\mathrm{products}} \dot{E} \quad (20)$$

and

$$\dot{L}_{\mathrm{ex}} = \sum_{\mathrm{inputs}} \dot{\mathrm{E}}\mathrm{x} - \sum_{\mathrm{products}} \dot{\mathrm{E}}\mathrm{x} \quad (21)$$

where the summations are over all input streams and all product output streams.

Another parameter, $\dot{R}$ is defined as the ratio of thermodynamic loss rate L to capital cost K as follows:

$$\dot{R} = \frac{\dot{L}}{K} \tag{22}$$

The value of $\dot{R}$ generally depends on whether it is based on energy loss rate (in which case it is denoted $\dot{R}_{en}$), or exergy loss rate ($\dot{R}_{ex}$), as follows:

$$\dot{R}_{en} = \frac{\dot{L}_{en}}{K} \tag{23}$$

and

$$\dot{R}_{ex} = \frac{\dot{L}_{ex}}{K} \tag{24}$$

Values of the parameter $\dot{R}$ based on energy loss rate, and on total, internal and external exergy loss rates are considered. In investigating sets of $\dot{R}$-values, maximum ($\dot{R}_{max}$), minimum ($\dot{R}_{min}$), mean ($\dot{R}_m$), standard deviation (SD($\dot{R}$)) and coefficient of variation (CV($\dot{R}$)), which is the ratio of standard deviation to mean, are considered.

3. Wind energy-related relations including exergetic aspects

In the design and performance assessment of wind energy systems, the relations given in Section 2 may be used to write mass, energy, exergy and exergoeconomic balance relations. In addition, the following ones may be applied to wind energy systems considered.

3.1. Energetic relations

Wind energy E is the kinetic energy of a flow of air of mass m at a speed V. The mass m is difficult to measure and can be expressed in terms of volume V through its density $\rho = m/V$. The volume can be expressed as $V = AL$ where A is the cross-sectional area perpendicular to the flow and L is the horizontal distance. Physically, $L = Vt$ and wind energy can be expressed as [30]

$$E = \frac{1}{2}\rho A t V^3 \tag{25}$$

The energy efficiency of a wind turbine is usually characterized by its power coefficient, as given below, with a maximum value of C_p as 0.5926 according to the Betz criterion [31].

$$C_p = \frac{\dot{W}_{act}}{\eta_{mech}\eta_{alternator}\dot{W}_a} \tag{26a}$$

with

$$\dot{W}_{act} = V_{LL} I \cos\psi \tag{26b}$$

and

$$\dot{W}_a = 0.5\rho\pi R^2 V_r{}^3 \tag{26c}$$

where $\dot{W}_{act}$ is the actual power (active power at generator output) and $\dot{W}_a$ is the actual power calculated by Eq. (26c), while due to some electrical and mechanical equipment losses the corresponding efficiencies are included.

Any measured wind velocity value can be estimated for different height by using the following Hellmann equation [31]:

$$V_r = V_{ref}\left[\frac{H}{H_{ref}}\right]^{\mu} \tag{27}$$

where V_{ref} is the wind velocity at a reference height and μ is the Hellmann coefficient.

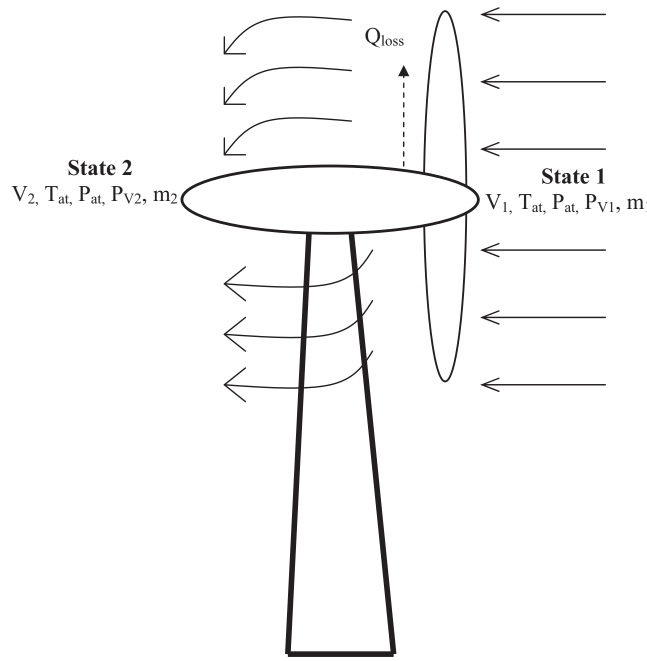

Fig. 1. Wind turbine and representative wind energy input and output variables (modified from Ref. [34]).

3.2. Exergetic relations

The exergy of fluid currents is entirely due to the kinetic energy of the fluid. The maximum work is extracted from a moving fluid when the velocity is brought to zero relative to the reference state. The kinetic energy of the fluid and its exergy (availability) have the same numerical value [32].

$$\psi_f = \frac{1}{2}\rho V^3 \tag{28}$$

where ρ is the density of the wind and V is the wind speed.

Exergy analysis includes the flow irreversibilities associated with the system. The exergy balance equation in the rate form can be expressed as

$$\dot{E}x_1 = \dot{W}_{out} + \dot{E}x_2 + \dot{E}x_{dest} \tag{29}$$

where $\dot{E}x_{dest}$ represents the exergy destruction rate associated with the process. It is a representative measure of the irreversibilities involved with the process. This methodology offers a useful alternative measure of turbine efficiency that includes the irreversibilities, which were not included in the first law analysis. The exergy rate of flow, $\dot{E}x_{flow}$, can be defined as the maximum attainable work acquired as the air flows through the turbine. The relevant terms include physical and kinetic exergy [33]

$$\dot{E}x_{flow} = \dot{E}x_{PH} + \dot{E}x_{KE} \tag{30}$$

The retardation of wind passing through a windmill occurs in two stages, before and after its passage through the windmill rotor [30]. Provided that a mass m is air passing through the rotor per unit time (or mass flow rate of air, $\dot{m}$), the rate of momentum change is $m(V_1 - V_2)$, which is equal to the resulting thrust. Here, V_1 and V_2 represent upwind and downwind speeds at a considerable distance from the rotor, as shown in Fig. 1 [34]. So, the physical and total exergy for wind energy can be expressed as follows, respectively [30]:

$$Ex_{PH} = \dot{m}C_p(T_2 - T_1) + \dot{m}T_{at}\left[C_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{P_2}{P_1}\right) - \frac{Q_{loss}}{\dot{m}T_{at}}\right] \tag{31}$$

$$Ex_{flow,total} = E_{generated} + \dot{m}C_p(T_2 - T_1) + \dot{m}T_{at}$$

$$\times\left[C_p \ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{P_2}{P_1}\right) - \frac{Q_{loss}}{\dot{m}T_{at}}\right] \quad (32)$$

with

$$Q_{loss} = \dot{m}C_p(T_{at} - T_{average}) \quad (33)$$

where the first term on the right side of this equation is the generated electricity, while the second and third parts are enthalpy and entropy contributions, respectively. Here, $\dot{m}$ is the mass flow of air, T_1 is the wind chill temperature at the input to the wind turbine, T_2 is the wind chill temperature at the exit of the wind turbine, T_{at} is the atmospheric temperature, P_2 is the pressure at the exit of the wind turbine for a wind speed V_2 and P_1 is the pressure at the inlet of the wind turbine for a wind speed V_1, Q_{loss} represents heat losses of wind turbine and $T_{average}$ is the mean value of input and output.

The present wind-chill expression is given by

$$T_{windch} = 35.74 + 0.6215T_{air} - 35.75(V^{0.16}) + 0.4274T_{air}(V^{0.16}) \quad (34)$$

where the wind chill temperature T_{windch} is in °F and wind speed V is in mph [30].

The kinetic component of the flow exergy is equivalent to the difference of kinetic energy through the turbine. The change in kinetic energy can also be expressed by the work output of the turbine, as indicated in Eq. (32) [33].

3.3. Energy and exergy efficiency relations

The expressions for energy (η) and exergy (ε) efficiencies for the principal types of processes considered in the present study are based on the following definitions [30,35]:

$$\eta = \frac{\text{energy in products}}{\text{total energy input}} \quad (35)$$

$$\varepsilon = \frac{\text{exergy in products}}{\text{total exergy input}} \quad (36)$$

where exergy efficiencies can often be written as a function of the corresponding energy efficiencies. Note that the exergy efficiency frequently gives a finer understanding of performance than the energy efficiency. The exergy efficiency weights energy flows by accounting for each in terms of usefulness. The exergy efficiency stresses that both external losses and internal irreversibilities need to be dealt with to improve efficiency. In many cases, the internal irreversibilities are more significant and more difficult to deal with than external losses.

Work production: Electric work production processes produce shaft work W and the efficiencies for shaft work production from electricity through wind energy system are

$$\eta_{e,m} = \frac{W}{W_e} \quad (37)$$

$$\varepsilon_{e,m} = \frac{E^W}{E^{W_e}} = \frac{W}{W_e} = \eta_{e,m} \quad (38)$$

Electricity generation: The efficiencies for electricity generation through wind energy system are

$$\eta_{e,f} = \frac{W_e}{m_f H_f} \quad (39)$$

$$\varepsilon_{e,f} = \frac{E^{W_e}}{m_f \beta_f H_f} \cong \eta_{e,f} \quad (40)$$

Therefore, the exergy efficiencies for electricity generation process can be taken as equivalent to the corresponding energy efficiencies.

Kinetic energy production: The efficiencies for the fossil fuel-driven and wind-driven kinetic energy production processes, which produces a change in kinetic energy Δke in a stream of matter m_s, are as follows [30,35]:

$$\eta_{KN,f} = \frac{m_s \Delta ke_s}{m_f H_f} \quad (41)$$

$$\varepsilon_{KN,f} = \frac{m_s \Delta ke_s}{m_f \beta_f H_f} \cong \eta_{KN,f} \quad (42)$$

The exergetic efficiency of a turbine is defined as a measure of how well the stream exergy of the fluid is converted into inverter work output. Applying this to the wind turbine, the following exergy efficiency relation may be obtained [31].

$$\varepsilon = \frac{W_e}{W_u} = \frac{W_e}{Ex_1 - Ex_2} \quad (43)$$

Xydis et al. [36] proposed the following exergy efficiency relation in % for evaluating the performance of wind farms, including the topographic & wake Losses, electrical losses, wind turbine technical availability losses, and air density losses

$$\varepsilon_{WF} = \frac{AEP_{net}}{8760P_{inst}}100 \quad (44)$$

and the capacity factor (CF), excluding the topographic and wake losses, electrical losses, wind turbine technical availability losses, and air density losses

$$CF_{WF} = \frac{AEP_{gross}}{8760P_{inst}}100 \quad (45)$$

where AEP_{net} and AEP_{gross} are the net and gross energies produced (Annual Energy Production) in MWh, respectively, while 8760 h are the total hours within a year and P_{inst} is the installed capacity of the wind farm in MW. In this context, it is also reported that the concept of "exergetic capacity factor" could indicate better the meaning of the real capacity factor of each wind farm in the means of identification of the actual use of energy.

Wind turbine's energy and exergy efficiency values may be also calculated using the following relations, respectively [37]:

$$\eta_s = \frac{P_e}{P_{KN}} = \frac{\dot{P}_{out}}{(1/2)\dot{m}V^2} = \frac{\dot{P}_{out}}{(1/2)\rho AV^3} \quad (46)$$

$$\varepsilon_{WT} = \frac{E_e}{E_{KN}} = \frac{W_e(Wh)}{P_{wind}8760h} = \frac{W_{elec}(Wh)}{8760(1/2)\rho AV^3} \quad (47)$$

It is also reported as follows [37]: It is well known that a wind turbine cannot exploit the complete power of wind. Energy efficiency of a wind turbine is affected by three efficiency factors explained below:

- *Power coefficient* (C_p): According to the Betz law, a wind turbine can exploit up to 59.3% (16/27) of wind energy.
- *Electric generator efficiency* (η_g): This can approach to 90–95% or even more for inductive generators connected to the electric network.
- *Wind turbine's sub-systems efficiency* (η_b): Frictions between the rotor turning part and the rolling bearings occur and lead to the heat production, which the cooling liquid absorbs from the gearing box, the generator and the other elements. Exergy losses also appear also in electronic devices, which contribute in the smooth wind turbine's start and operation, and consume 1–2% of the energy. η_b can totally approach to 95% for modern, technologically developed wind turbines.

Finally, in the exergy output of a wind turbine or a wind park, the availability factor, which refers to the right installation, maintenance and operation of the facility, should be included. A well organized wind park can reach 95–98%, while the output efficiency

decreases, for cases of insufficient maintenance, up to the 60–70% [37].

3.4. Exergoeconomic relations

The EXCEM model for wind energy systems may be modeled as follows. Using Eqs. (20) and (26a–c), the energy loss rate may be obtained from the following relation [31]:

$$\dot{L}_{\mathrm{en}} = \eta_{\mathrm{m}}\eta_{\mathrm{alternator}}\dot{W}_{\mathrm{a}} - \dot{W}_{\mathrm{act}} \tag{48}$$

Using Eq. (21), the exergy loss rate may be written as follows [31]:

$$\dot{L}_{\mathrm{ex}} = \dot{W}_{\mathrm{u}} - \dot{W}_{\mathrm{e}} \tag{49}$$

with

$$\dot{W}_{\mathrm{u}} = \dot{\mathrm{E}}\mathrm{x}_1 - \dot{\mathrm{E}}\mathrm{x}_2 \tag{50}$$

where $\dot{W}_{\mathrm{u}}$ is the useful work rate and $\dot{W}_{\mathrm{e}}$ is the work rate (power) at inverter output, while the flow exergy rates ($\mathrm{E}\dot{\mathrm{x}}_1$, $\mathrm{E}\dot{\mathrm{x}}_2$) may be calculated using Eq. (6a) or Eq. (6b) based upon the assumptions made.

4. Reviewing and classifying the previously conducted studies on exergetic and exergoeconomic analysis and assessment of wind energy systems

4.1. Exergetic analysis and assessment

4.1.1. Wind energy systems

Koroneos et al. [38] presented two diagrams where utilization of the wind's potential in relation to the wind speed and exergy losses in the different components of a wind turbine (i.e., rotor, gearbox and generator) were included. They concluded that "according to Betz's law, wind turbine can take advantage of up to 60% of the power of the wind. Nevertheless, in practice, their efficiency is about 40% for quite high wind speeds. The rest of the energy density of the wind not obtainable is exergy loss. This exergy loss appears mainly as heat. It is attributed to the friction between the rotor shaft and the bearings, the heat that the cooling fluid abducts from the gearbox, the heat that the cooling fluid of the generator abducts from it and the thyristors, which assist in smooth starting of the turbine and which lose 1–2% of the energy that passes through them."

As for the studies conducted on exergetic assessment of wind energy systems, Sahin et al. [34] developed a new exergy formulation for wind energy, which was more realistic and also accounted for the thermodynamic quantities enthalpy and entropy. This was the first attempt in deriving the relations for the exergetic assessment of wind energy systems. Sahin et al. [34] presented mean energy and exergy efficiencies as a function of wind speed, as shown in Fig. 2 [34]. This figure emphasized the differences between the efficiencies, and indicated the over-estimation provided by energy efficiencies. The relative differences between energy efficiency and exergy efficiency, where exergy efficiency was taken as the base value, were given in the same figure. It is obvious from this figure that the relative difference was lowest at a wind speed of about 7 m/s and increased at lower and higher wind speeds. These relative differences implied that the exergy efficiency approach should be applied to wind energy systems for better understanding. It was also determined that the average differences between energy and exergy efficiencies were approximately 40% at low wind speeds and up to approximately 55% at high wind speeds.

Ozgener and Ozgener [39] performed exergy analysis of a wind turbine system (1.5 kW) located in Solar Energy Institute of Ege University (latitude 38.24 N, longitude 27.50 E), Izmir, Turkey. They

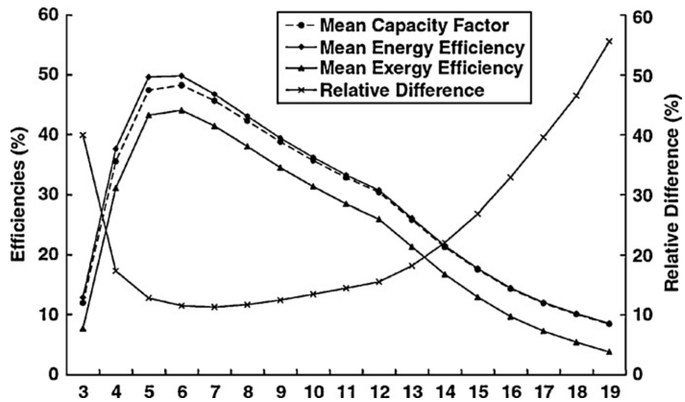

Fig. 2. Mean exergy and energy efficiencies, and percent differences between these values as a function of wind speed [34].

investigated the variation of exergy efficiency values of the wind turbine system (three-bladed 3-m diameter horizontal axis) with various blowing air temperatures varying between 0 and 20 °C (with an increment of 5 °C), as shown in Fig. 3 [39]. It is seen from the figure that exergy efficiency value changed between 0 and 89%, while it was maximum at 12 m/s with a temperature of 20 °C. This figure also indicated the effect of blowing air temperatures on the exergy efficiencies. As the blowing air temperature increased about 20 °C, the exergy efficiency increased from 24.82 to 89.55%. It was also reported that exergy efficiency varied between 0 and 48.7% at different wind speeds based on a dead state temperature of 25 °C and atmospheric pressure of 101.325 kPa, considering pressure differences between state points.

Ahmadi and Ehyaei [40] investigated the exergy analysis by considering the physical, chemical and kinetic exergies through a wind turbine. After the modeling of entropy production, the Bergey Excel-S wind turbine was optimized in two cities of Iran. Fig. 5 [36] illustrates variation of the average produced power and entropy generation rate by the Bergey Excel-S wind turbine with rated speed based on the annual average input wind data at Manjil. Assuming that the design conditions such as wind data, temperature and pressure are kept constant, the entropy generation rate is a function of cut-in, furling and rated wind turbine speeds and average produced power. Regarding Fig. 4 [40] and the functional property, the optimum value of cut-in, rated and furling wind turbine speeds would be 3.4, 14.8 and 16.72 m/s, respectively. By selecting the above quantity for the specification of a Bergey Excel-S wind turbine, the annual average produced power would increase by about 9.7%, and the average entropy generation rate would decrease by 0.7% in comparison to the Bergey Excel-S wind

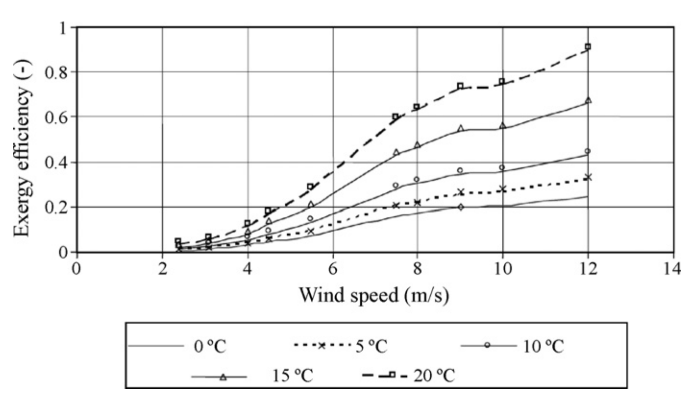

Fig. 3. Exergy efficiency of the wind turbine system, three-bladed 3 m diameter horizontal axis, according to different temperatures of blowing air (dead state conditions: 25 °C and 101.325 kPa) [39].

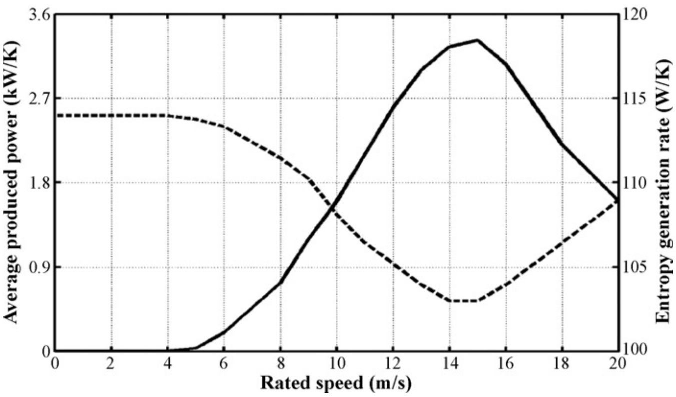

Fig. 4. Variation of the average produced power and entropy generation rate by the Bergey Excel-S wind turbine with rated speed based on the annual average input wind data at Manjil [40].

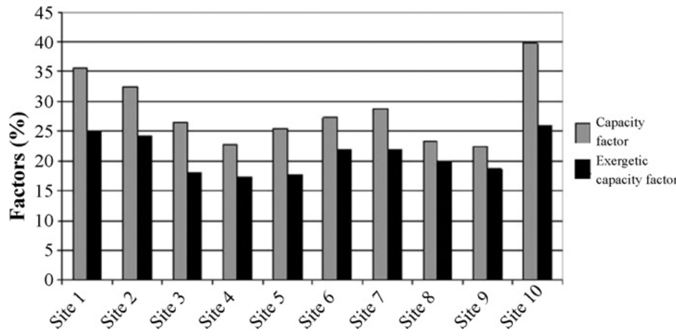

Fig. 5. Variation of capacity factors and exergetic capacity factors at the 10 proposed wind turbine sites in the Central Peloponnese, Greece [36].

turbine in the previous state. The results also indicated that, on the base of the annual average wind data, if the wind turbine would be installed in Tehran, by varying the cut in, rated and furling speeds from 3.1, 13.8 and 15.6 to 2.53, 11 and 12.43 (m/s), respectively, the annual average produced power could increase by about 20%, while the entropy generation could decrease about 76.9%. The following concluding remarks have also been reported: (i) the input wind data affect the optimum characteristics of a wind turbine, so the annual average wind data should be considered to optimize it in the maximum power produced through the year, (ii) the maximum point of the annual average power produced by a wind turbine coincides with the minimum entropy generation rate, and (iii) the city with greater annual average wind speed (Manjil), has greater optimum value of cut-in, rated and furling speeds in comparison to the city which has a lower annual average wind speed (Tehran), and (iv) the optimum approach is more effective in the city with low yearly speed wind (Tehran).

Xydis et al. [36] investigated the wind potential of Central Peloponnese in Greece and utilized exergy analysis method as a wind farm sitting selection tool. They also studied the wind speed of the chosen regions of Central Peloponnese and correlated based on the measurements of three specific sites in the wider area using a software based prognostic model enabling intercomparisons of crosspredictions among these sites. The exergy analysis method implemented in this innovative wind speed forecasting model was used to identify the actual use of energy from the existing available energy and to evaluate the proposed sites appropriate for wind farm development ending up to an accurate wind map of the area. In this regard, it concluded that the exergy analysis could be used to measure and evaluate interconnected wind farms considering their various losses (topographic and wake losses, electrical losses, wind turbine technical availability losses, and air density losses), while it would be a very useful tool to reveal the maximum useful work that can be derived from a wind farm. Fig. 5 illustrates a variation of exergetic capacity factor and capacity factor at the 10 proposed wind turbine sites in the Central Peloponnese, Greece, which were obtained using Eqs. (44) and (45), respectively. The losses of these sites ranged from 14.99 to 35.09%, while their percentage breakdown was as follows: topographic and wake losses: 0.60–7.27, electrical losses: 6–15.3, wind turbine technical availability losses: 3, and air density losses: 5.49–16.79. The AEP values varied between 12.082 and 18.111 GWh with wind velocities ranging from 5.59 to 7.98 m/s. It is obvious from this figure that the sites with lower capacity factor (i.e., sites 8, 9) had higher exergy efficiency values.

Pope et al. [33] performed an energy and exergy analysis of four different wind power systems, including both horizontal and vertical axis wind turbines. They encompassed significant variability in turbine designs and operating parameters through the selection of systems. In particular, two airfoils (NACA 63(2)-215 and FX 63-137) commonly used in horizontal axis wind turbines were compared with two vertical axis wind turbines (VAWTs). A Savonius design and Zephyr VAWT benefit from operational attributes in wind conditions that are unsuitable for airfoil type designs. Each system was also analyzed using energy and exergy analysis methods. The aerodynamic performance of each system was numerically analyzed by computational fluid dynamics software, FLUENT. A difference in energy and exergy efficiencies of between 50 and 53% was predicted for the airfoil systems, whereas 44–55% differences are predicted for the VAWT systems. Pope et al. also illustrated the results of exergy analysis of the Benz limit in Fig. 6 [33]. They reported that the theoretical maximum energy efficiency is obtained with the Benz limit. With the first law, the Benz limit is a constant value independent of operating conditions. However, combining the Benz limit theory with second law analysis provides a theoretical maximum efficiency that includes the effect of irreversibilities, resulting in a dependence on design and operating conditions. Defining it here as $0.59(\dot{W}_{out}t)/\dot{E}x_{flow}$ the second law Benz limit with both methods of obtaining $\dot{E}x_{flow}$ (i.e., ε_B and $\varepsilon_{2,B}$) is presented. Significant variability between the VAWTs and the airfoils is predicted by ε_B from 29 to 59%, while the range of $\varepsilon_{2,B}$ is only 28–32%. Table 1 summarizes the energy (first law) and exergy (second law) efficiencies, predicted for the reference operating conditions.

Baskut et al. [41] reported exergy efficiency results of the wind turbine power plants. They investigated effects of meteorological variables, such as air density, pressure difference between state points, humidity, and ambient temperature, on exergy efficiency, while the results obtained during the month of November 2007 till September 2008 were given and discussed. Some key param-

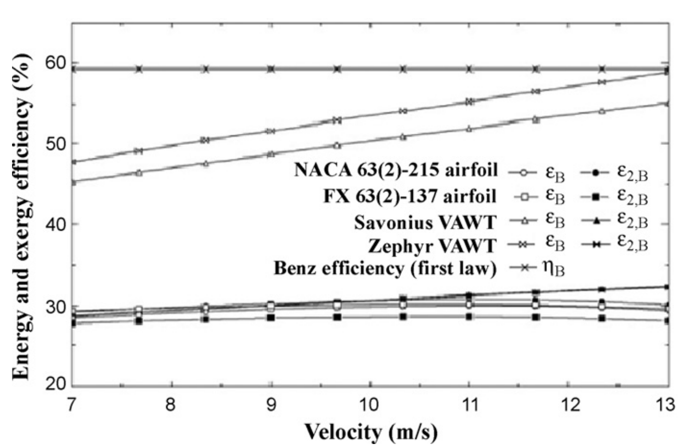

Fig. 6. Energy and exergy efficiencies based on Benz efficiencies [33].

Table 1
Various predicted energy (η) and exergy (ε) efficiency values according to various types of wind turbines in % [33].

Type	η	ε	ε_2	ε_B	$\varepsilon_{2,B}$	η_{KE}	ε_{KE}	$\eta_{KE,2}$
NACA 63(2)-215 airfoil	44	21	22	29	30	39	19	20
FX 63-137 airfoil	47	23	22	30	28	59	29	27
Savonius VAWT	18	17	10	55	32	94	87	51
Zephyr VAWT	11	10	6	59	32	93	93	59

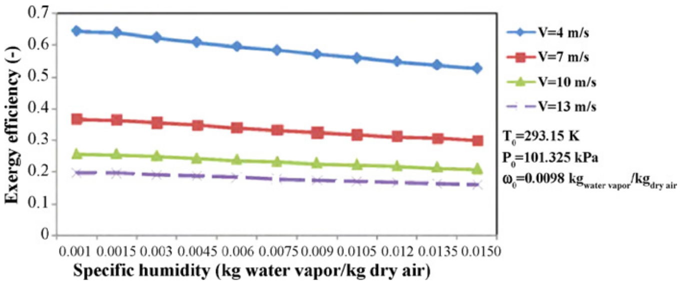

Fig. 7. Variation of exergy efficiency with specific humidity at different wind speeds [41].

eters were also given monthly for the three turbines, which had average wind speeds of 6.1–9 m/s, monthly operation hours of 471–698 h and monthly energy production values of 76, 502–181, 894. Exergy efficiency values varied between 23 and 27%, while temperatures changed from 268.15 to 308.15 K with air densities of 1.368–1.146 kg/m^3. A variation of exergy efficiency with specific humidity at different wind speeds is indicated in Fig. 7 [41], where specific humidity values are taken from the psychrometric chart for P = 1 atm. It is seen from this figure that exergy efficiency decreases with increasing the specific humidity values, as expected. In the same specific humidity, as the wind velocities increase, exergy efficiencies decrease. The following main conclusions have also been reported: (i) as both the pressure difference between the inlet and outlet of the turbine and humidity increase, the exergy efficiency decreases, and (ii) exergy analysis indicates that the meteorological variables should be taken into consideration at the planning stage of wind turbine power plans.

4.1.2. Wind powered systems

Romero-Terneroa et al. [42] quantified the exergy efficiency of a wind-powered seawater reverse osmosis system (WPRO) using exergy analysis method. Their exergetic efficiency relation was based on Eq. (17), namely a ratio of exergetic product to exergetic fuel. Fig. 8 [42] illustrates a flow chart of the whole system. As seen from this figure, inlet wind exergy flow, W, is the wind power (WP) exergetic fuel and the power generated by the wind turbines is the WP exergetic product. This power and the seawater exergy flow,

Table 2
A comparison between efficient and not functional wind parks in terms of exergy losses (Input: wind energy) (adapted from [37]).

Description of output	Output values in % according to type of wind park	
	Efficient	Not functional
Betz law losses	40.7	40.7
Electrical generator losses	5–10	5–10
Subsystem losses	5	5
Availability losses	1–5	25–30
Electrical energy	45–50	25–30

SW, constitute the RO fuel. Then, the inlet exergy flows of wind (W) and seawater (SW) are the WPRO fuel. The fresh water exergy flow, P, is the product of both the RO and WPRO systems. Finally, brine B and outlet wind W' exergy flows are losses. An exergy efficiency value of about 29% was obtained for the WP system with an inlet wind power of 1983 kW and a generated power of 566 kW. In terms of exergy destruction, the WPRO rate was 1483 kW, 70% of which was due to the WP system (1032 kW), while the remaining 30% (451 kW) was destroyed in the RO system.

Koroneos and Katopodi [37], as a second objective of their study, investigated and analyzed thermodynamically, the efficiency along the hydrogen and electricity production cycle, starting from the kinetic energy of the wind. They also mapped and the hydrogen and electricity production cycle mathematically calculated the change of exergy due to losses at different points using the data of Greece, specifically the island of Crete. It was concluded that there was a two fold change in exergetic efficiency along both paths. Table 2 compares the exergy losses between an efficient and an unefficient wind park. It is clear from this tablet that there is an excellent exploitation of wind energy for an organized park that operates efficiently and effectively. It is also reported that the availability factor is the most important one that defines the output of a wind park. However, the correspondent technology used also plays a big role (i.e., pitch or stall control and synchronous or asynchronous generator).

4.1.3. Developing wind exergy maps

As far as developing wind exergy maps is concerned, only one study has been done up to date in the open literature to the best of the authors' knowledge. In this context, Sahin et al. [30] introduced a new concept in the area of wind energy through new spatio-temporal exergy maps and studied both energetic and exergetic aspects of wind energy in more detail. They also presented energy and exergy efficiencies in the form of geostatistical maps for 21 climatic stations in the province of Ontario, Canada over a period of four months. Exergy maps provided a new and original approach as well as more meaningful and useful information than energy analysis regarding the efficiency, losses and performance for wind

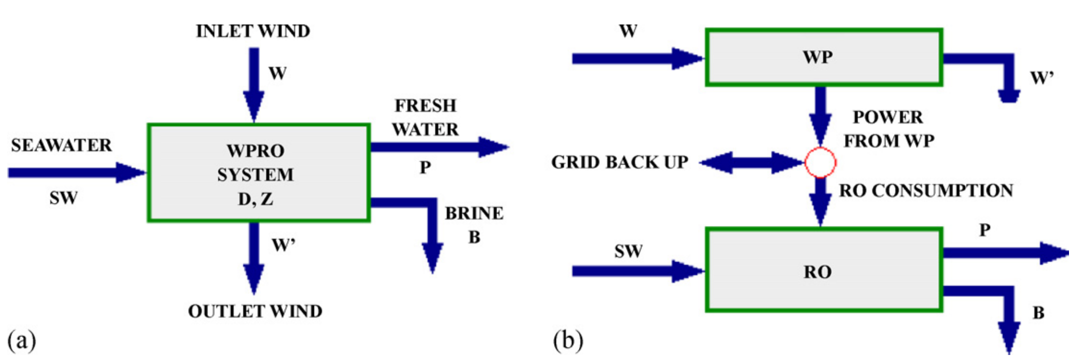

Fig. 8. (a) Flow chart of fresh water generated from seawater and wind with a null annual mean energy backup from the grid. The WPRO system is characterized by D, exergy destruction, and Z, investment, O&M (operational and maintenance) and replacement costs; (b) WP and RO subsystems [42].

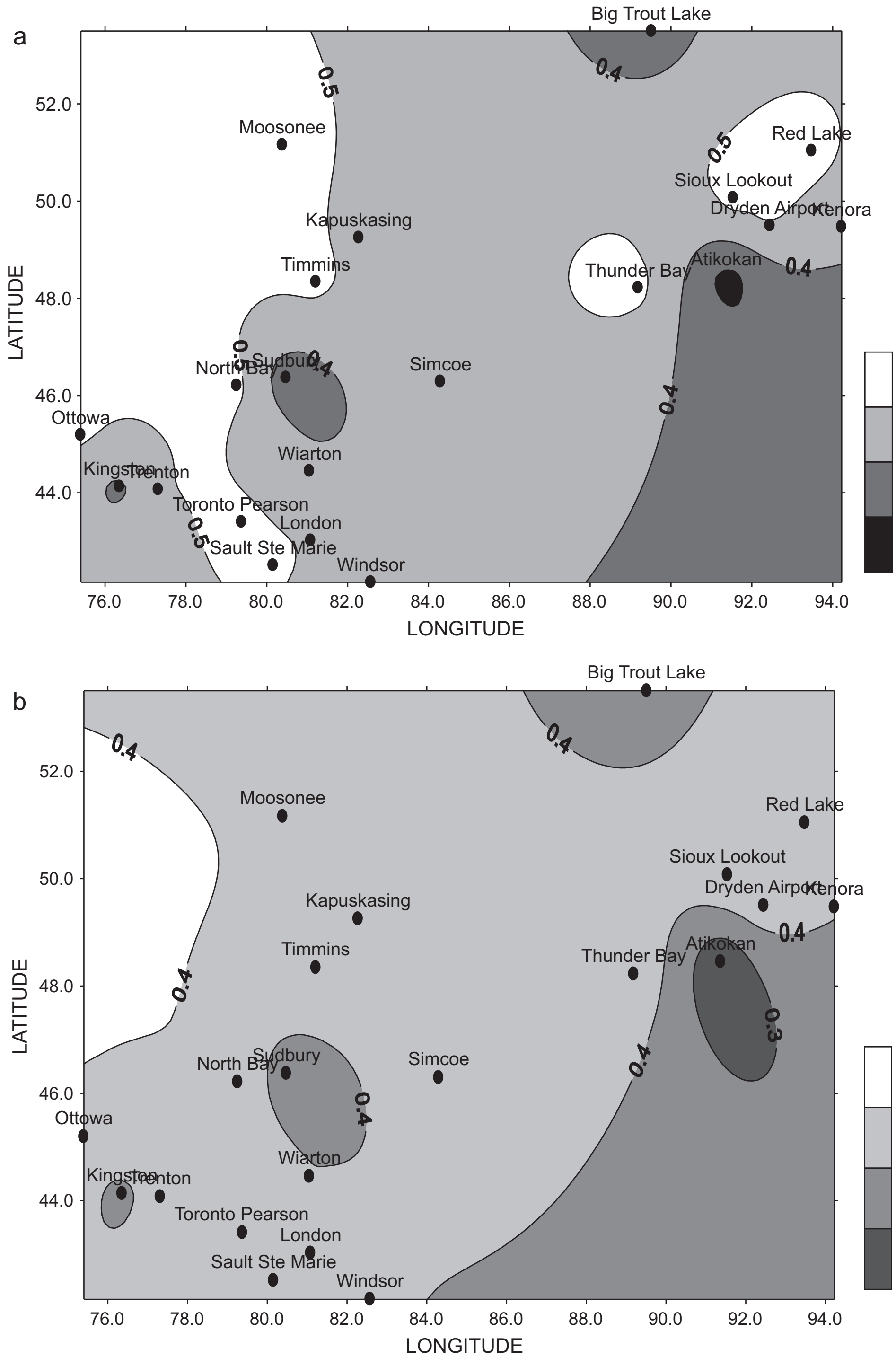

Fig. 9. (a) October energy efficiency map for Ontario [30]. (b) October exergy efficiency map for Ontario [30].

turbines. Energy and exergy efficiencies were estimated using measured generated power data. Cut-in and cut-out wind speed values were 3.5 and 21 m/s, respectively. It was seen that capacity factors of the wind turbine system considered were very high even if without considering enthalpy values. The capacity factor was approximately 45% for wind speeds of 8–11 m/s. Maps of estimated efficiencies for 21 stations in Ontario were subsequently developed. In their comprehensive study, 30-year average wind speed, temperature and pressure data were utilized. Wind speed values were interpolated from 10 to 30 m. Output electricity power data for a 100 kW wind turbine, which was more convenient for rural area renewable energy application, with a rotor diameter at 18 m and hub height 30 m, were given. January, April, July and October geostatistical spatio-temporal maps were developed and discussed. Fig. 9a and b [30] indicate energy and exergy efficiency maps for Ontario in the month of October. These maps were intended to indicate the differences between energy and exergy efficiencies of a specific wind turbine system at the same conditions through exergy analysis. Energy efficiencies were grouped into two main clusters. Topographical conditions cause some localized effects at these stations in October (Fig. 9a). Exergy efficiencies were lower than energy efficiencies during this month. It was seen that one of

the highest energy efficiency areas, which was observed in western Ontario, was less significant based on exergy (Fig. 9b). Without summer topographical heating, the relative differences between these efficiencies were low during October in most parts of Ontario. But wind chill became more appreciable during this month. The results indicated that aerial differences between energy and exergy efficiencies were approximately to 20–24% at low wind speeds and approximately to 10–15% at high wind speeds.

Based on reviewing the previously conducted studies on exergetic analysis and assessment of wind energy-related systems, Table 3 is prepared by the authors. As can be seen from this table, almost in the last five years, the new modeling and assessment studies have been conducted by limited investigators, while wind exergy maps have not been developed by other investigators for various countries yet [30,33,34,36–42].

4.2. Exergoeconomic analysis and assessment

Romero-Terneroa et al. also [42] quantified the exergoeconomic cost of a WPRO system indicated in Fig. 8. Exergoeconomic cost of the product was defined as a sum of exergoeconomic cost of fuel and fixed costs. Unit exergoeconomic costs of the product (c€/MJ) for WP, RO and WPRO were reported to be 1.21, 13.1 and 13.1, respectively. The ratio of discounted rate of fixed costs (2.65 c€/s) to the exergy rate of the product (202 kW) yielded the unit exergoeconomic cost of the product: 13.1 c€/MJ.

It was concluded that wind power was cost-effective up to an amount slightly less than 1.22 c€/MJ (4.4 c€/kWh).

A comprehensive exergoeconomic analysis of a 1.5 kW wind turbine system through EXCEM was performed by Ozgener et al. [31]. The relations between capital costs and thermodynamic losses for the system components were investigated. The results indicated that while the ratio of energy loss rate to capital cost (R_{en}) varied between 0.007 and 0.813 at different wind speeds, the ratio of exergy loss rate to capital cost (R_{ex}) changed from 0.006 to 0.411. In addition, the maximum R_{en} and R_{ex} values were obtained at a wind speed of 12 m/s. Furthermore, a parametric study was conducted to investigate how varying wind speed would affect the exergoeconomic parameters of the wind turbine system and to develop a correlation between the ratio of thermodynamic loss rate to capital cost and wind speed for practical applications of wind energy systems. It was also reported that for any technology, it appears that the design of a device may be made more successful if it is modified, so that its value of R_{ex} approaches appropriate R_{ex}. A balance is obtained between exergy loss and capital cost in real systems. If successful technologies conform to an appropriate R_{ex}, then it follows that technologies which fail in the marketplace may do so because they deviate too far from the appropriate R_{ex}. Thus research and development should perhaps strive to identify devices for which the difference between the values of R_{ex} is large, and develop ways to narrow the difference [25].

5. Possible future exergy-based investigations to be conducted

The following indices and methods, which have not been yet applied to wind energy systems to the best of the author's knowledge, are recommended for future studies on exergy-based wind energy systems.

5.1. Application of sustainability index

The sustainability factor [12], which is directly related to the exergetic efficiency aims at supplying clean and affordable energy resources to be used. The efficient use of these resources is also of great importance. Sustainability index (SI), which has been recently used by some investigators [43,44], can be formulated to be [12]:

$$\varepsilon = 1 - \frac{1}{\mathrm{SI}} \tag{18'}$$

5.2. Utilizing the Lowex approach

Energy consumption in the residential sector is one of the main parts of the total energy consumption in most countries. World-wide energy consumption by HVAC equipment in buildings ranges 16–50% of total energy consumption, depending on the countries and their sectoral energy use patterns [44,45]. Trends in energy demand for heating and cooling could, therefore, be very important for the development of the energy system. Of course, the key issue is how to make buildings energetically sustainable? Exergy as a thermodynamic analysis tool can help achieve this objective. The low exergy (LowEx) approach is one of these approaches, which may be used in sustainable buildings design. This approach is based on a pre-design analysis tool, which has been produced during ongoing work for the International Energy Agency (IEA) formed within the Energy Conservation in Buildings and Community Systems Programme (ECBCSP) Annex 37 to increase the understanding of exergy flows in buildings and to be able to find possibilities for further improvements in energy utilization in buildings. Its main objective is to constitute a sustainable built environment. Future buildings should be planned to use sustainable energy sources for HVAC applications. One characteristic of these energy sources is that only a relatively moderate temperature level can be reached, if reasonably efficient systems are desired [46].

Fig. 10 illustrates the energy flows in forms of primary and electricity for a building from primary energy transformation through the heat production system and a distribution system to a heating system, and from there, via the indoor air, across the building envelope to the surrounding air [43,46]. The system may be investigated in terms of two parts, namely the building part and energy supply part. Primary energy source is taken as fosil fuels and renewable energy sources.

The lowex approach has also been recently applied by some investigators to various renewable energy sources such as a heat pump heating system [47,48], a geothermal heating system [49]. The studies conducted up to date have not focused on the energy supply part, which is related to any kinds of wind energy systems.

5.3. Application of various conventional and advanced exergoeconomic analysis methods

Exergoeconomic (thermoeconomic) analysis, which is a combination of exergy and economics, is also very important for energy-related systems. Thermoeconomics is the branch of engineering that combines exergy analysis and economic principles to provide the system designer or operator with information not available through conventional energy analysis and economic evaluations, but crucial to the design and operation of a cost-effective system. Thermoeconomics can be considered as exergy-aided cost minimization [50]. A complete exergoeconomic analysis consists of three subanalyses, namely (i) an exergetic analysis, (ii) an economic analysis, and (iii) an exergy costing that leads to the exergoeconomic evaluation. The exergetic analysis is suitable for identifying the sources of irreversibilities as exergy can be destroyed or lost,while energy is always conserved. The exergoeconomic analysis is conducted with a system of balance equations, stated at the component level, and a general equation for the overall system [51]. In addition, in an advanced exergetic analysis, the exergy destruction within each system component is split into its avoidable/unavoidable and endogenous/exogenous parts. Finally a combination of these two splitting approaches provides unambigu-

Table 3
Reviewing and comparing exergetic analysis and assessment of wind energy-related systems [30,33,34,36–42].

Investigators	Year published	Type of investigation			System characteristics considered	Some exergetic assessments results and comments
		Wind exergy system	Wind powered system	Developing wind exergy maps		
Koroneos [38]	2003	√			Reporting the exergy losses in the different components of a wind turbine (i.e., rotor, gearbox and generator)	In practice, the efficiency of a wind turbine is about 40% for quite high wind speeds. The rest of the energy density of the wind not obtainable is exergy loss
Sahin et al. [34]	2006	√			First attempt in deriving the relations for the exergetic assessment of wind energy systems	The average differences between energy and exergy efficiencies were approximately 40% at low wind speeds and up to approximately 55% at high wind speeds
Ozgener and Ozgener [39]	2007	√			Performing exergy analysis of a wind turbine system (1.5 kW) based on actual operational data	Exergy efficiency value varied between 0 and 89%, while it was maximum at 12 m/s with a temperature of 20 °C
Ahmedi and Ehyaei [40]	2009	√			Investigating the exergy analysis by considering the physical, chemical and kinetic exergies through a wind turbine	If a wind turbine would be installed in Tehran (under the reported speeds), the annual average produced power could increase by about 20%, while the entropy generation could decrease about 76.9%
Xydis et al. [36]	2009	√			Investigating the wind potential of Central Peloponnese in Greece using exergy analysis method as well	The sites with lower capacity factor had higher exergy efficiency values
Pope et al. [33]	2010	√			Performing energy and exergy analyses of four different wind power systems, including both horizontal and vertical axis wind turbines	A difference in energy and exergy efficiencies of between 50 and 53% was predicted for the airfoil systems, whereas 44–55% differences for the vertical axis wind turbines systems
Baskut et al. [41]	2010	√			Investigating the effects of meteorological variables, such as air density, pressure difference between state points, humidity, and ambient temperature on exergy efficiency of wind turbine plants	Exergy efficiency values were in the range of 23–27%, while temperatures varied between 268.15–308.15 K with air densities of 1.368–1.146 kg/m^3
Romero-Ternero et al. [42]	2005		√		Quantifying the exergy efficiency of a wind-powered seawater reverse osmosis system (WPRO)	Exergy efficiency of the WPRO system was 10.2%, with the exergetic efficiencies of 28.6 and 35.7% for WP and RO subsystems, respectively
Koroneos and Katopodi [37]	2011		√		Mapping and mathematically calculating the change of exergy due to losses at different points of a hydrogen and electricity production cycle using the data of Greece, specifically the island of Crete	There was a two fold change in exergetic efficiency along both paths
Sahin et al. [30]	2006			√	First attempt in developing new spatio-temporal exergy maps	Aerial differences between energy and exergy efficiencies were approximately to 20–24% at low wind speeds and approximately to 10–15% at high wind speeds

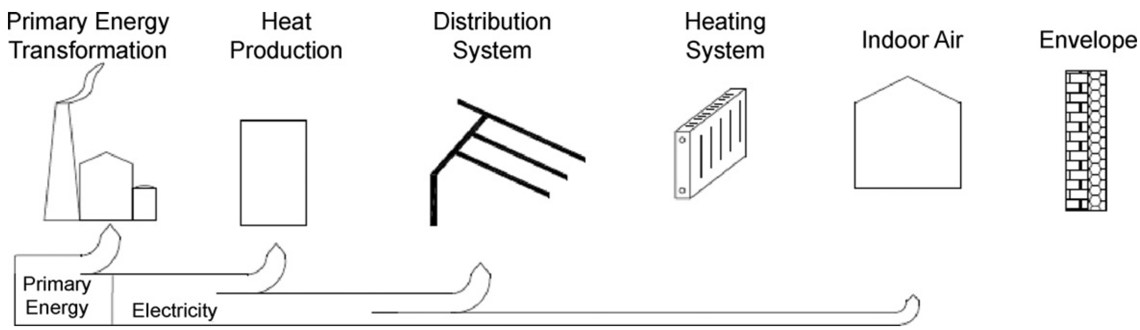

Fig. 10. Energy flows from primary energy transformation to the environment [43,46].

ous and valuable detailed information with respect to options for improving the overall efficiency. The information obtained from the advanced analysis allows engineers to better understand the interconnections among components and the potential for improving such systems [52].

As can be seen from the literature survey conducted here, only the EXCEM method as an exergoeconomic tool has been applied to wind energy systems. In the literature, there are also various types of exergoeconomic analysis methods. Among these, for example, the specific exergy cost (SPECO) method proposed by Lazzaretto Tsatsaronis [53] has been recently applied by Yildiz et al. [54] to calculate exergy-related parameters of hydrogen production from plasma gasification of sewage sludge and display cost flows for all streams and components. Petrakopoulou [51] also performed exergoeconomic and exergoenvironmental analyses of a combined cycle power plant. In this regard, various conventional and advanced exergoeconomic analysis methods may be applied to wind energy-related systems.

5.4. Wind classification based on exergy

In 1986 the DOE complied a wind energy resource atlas of the US to indicate areas potentially suitable for wind energy projects [55]. Since then, another studies have been conducted on that issue. This atlas established wind resource maps for estimating the renewable resource in terms of wind power classes, ranging from Class 1 (the lowest) to Class 7 (the highest). Each class represents a range of mean wind speeds at specified heights above the ground. These maps are utilized as very useful tools in the analysis of siting criteria for a wind park [56].

Taking the wind exergy maps developed by Sahin et al. [30] or specific exergy index proposed by Lee [57] as a new parameter for classification of geothermal resources by exergy, a new specific exergy index (SExI) may be investigated and developed for better classification and evaluation of wind exergy maps or wind energy-related systems.

5.5. Performing an exergetic lifecycle assessment

Given a satisfactory performance, there are three tools available to decision/policy mailers to evaluate the desirability of a specific product or technology. These tools are financial analysis, energy and exergy analyses. Financial analysis, based on cost of manufacture, installation, maintenance and operations, salvage, etc., and cost of energy, utilized/saved during the life of a product, enables the user to decide on adoption of product/technology. A corresponding energy analysis based on input energy (also as embodied energy) in manufacture, installation, maintenance and operations salvage (negative), etc., and energy output throughout the life of a product, enables the user to decide on desirability of product from point of view of energy security. These two analyses also provide a rational basis for steps, like subsidies, duty reduction, etc., for promoting the product/technology. In terms of global warming and the corresponding effects on the environment, an exergy analysis, as treated in this paper in more detail, indicates the desirability of the product/technology from the point of view of the environment. To put it briefly, financial, economic and exergy analyses provide a rational basis for policy decisions, derived from consideration of finance, energy security and environment [58]. In the literature there are some studies considering exergetic life cycle analysis method. For example, Fiaschi and Lombardi [59] utilized this method to assess the performance of an integrated gasifier combined cycle power plant with integrated CO_2–H_2S removal. Vivek et al. [58] performed a life cycle cost analysis of a hybrid photovoltaic-thermal water and air collector based on energy and exergy. In this context, the performance of various wind energy-related systems may be evaluated and compared using exergetic life cycle assessment method.

6. Conclusions

Among renewable energy sources, wind energy is a free, clean, and renewable source of energy, which will never run out, is of a big importance. This study comprehensively reviewed the studies conducted on exergetic and exergoeconomic analyses and assessments of wind energy-related systems. Some concluding remarks, which can be extracted from this study, are listed as follows:

(a) Exergy is a way to a sustainable development. In this regard, exergy analysis is a very useful tool, which can be successfully used in the design and performance evaluation of wind energy as well as all energy-related systems. More generally, the exergy approach provides useful results for wind energy systems, while the tools included here could have widespread applications.
(b) Exergoeconomic studies may provide some key information for the people working in the area for better design, analysis, performance improvement, and operation of the wind energy systems.
(c) New energy and exergy efficiency maps of the wind energy generating system were introduced in 2006 for the first time to provide a common basis for regional assessments and interpretations [30]. Since then, another study using this methodology has not yet appeared in the open literature. It was also reported that the relative differences between energy and exergy efficiencies were highest in winter and lowest in summer, while exergy efficiencies were lower than energy efficiencies for each station for every month considered.
(d) A new exergy formulation for wind energy was developed in 2006 for the first time to exergetically assess wind energy systems by accounting for the thermodynamic quantities enthalpy and entropy [34].

(e) Although various limited studies have been undertaken to perform exergy analyses of wind energy systems, there was one study based on the investigators' measurements obtained from a wind turbine system of 1.5 kW [39].
(f) The effects of meteorological variables, such as air density, pressure difference between state points, humidity, and ambient temperature on exergy efficiency of wind turbine power plants were investigated in 2010, while exergy efficiency values ranging from 23 to 27% have been reported [41].
(g) The exergy efficiencies of the reviewed wind energy systems ranged from 23 to 89% depending on the system considered and dead state temperatures.
(h) The first comprehensive exergoeconomic analysis of a 1.5 kW wind turbine system through EXCEM was performed in 2009 [31].
(i) Based on the current literature survey, most studies have focused on the energetic aspects of wind energy-related systems, while application of the exergetic and exergonomic tools (including the conventional and advanced methods) reported here is very low in numbers.
(j) Various novel studies on wind energy systems, such as wind classification based on exergy, performing exergetic and exergoeconomic lifecycle assessment, utilization of advanced exergetic and exergoeconomic analysis methods, may be recommended for future works.
(k) As a conclusion, the authors expect that the analyses and assessments reported here will provide the investigators with knowledge about how effective and efficient today's state-of-the-art wind energy systems may be designed, operated and tested.

References

[1] Doukas H, Papadopoulou AG, Nychtis C, Psarras J, van Beeck N. Energy research and technology development data collection strategies: The case of Greece. Renew Sustain Energy Rev 2009;13:682–8.
[2] European Commission. Action plan for energy efficiency: realizing the potential. COM(2006)545 final; October 19, 2006.
[3] Omer AB. Energy, environment and sustainable development. Renew Sustain Energy Rev 2008;12:2265–300.
[4] Hepbasli A, Ozgener O. A review on the development of wind energy in Turkey. Renew Sustain Energy Rev 2004;8(3):257–76.
[5] Rehman S, Ahmad A, Al-Hadhrami LM. Development and economic assessment of a grid connected 20 MW installed capacity wind farm. Renew Sustain Energy Rev 2011;15:833–8.
[6] Milford E. World market update: Strong growth, record installations. BTM Wind Market Report, http://www.renewableenergyworld.com/rea/news/article/2010/07/btm-wind-market-report; July 20, 2010 [accessed on 8 November 2010].
[7] Hepbasli A. A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renew Sustain Energy Rev 2008;12(3):593–661.
[8] Obara S, Hepbasli A. Compound energy systems: optimal operation methods. Cambridge, UK: The Royal Society of Chemistry; 2010.
[9] Dincer I. The role of exergy in energy policy making. Energy Policy 2002;30:137–49.
[10] Saidur R, Sattar MA, Masjuki HH, Ahmed S, Hashim U. An estimation of the energy and exergy efficiencies for the energy resources consumption in the transportation sector in Malaysia. Energy Policy 2007;35:4018–26.
[11] Rosen MA, Dincer I, Kanoglu M. Role of exergy in increasing efficiency and sustainability and reducing environmental impact. Energy Policy 2008;36:128–37.
[12] Rosen MA, Dincer I. Exergy methods for assessing and comparing thermal storage systems. Int J Energy Res 2003;27(4):415–30.
[13] Hepbasli A, review on energetic A. exergetic and exergoeconomic aspects of geothermal district heating systems (GDHSs). Energy Convers Manage 2010;51(10):2041–61.
[14] Chang H. Exergy analysis and exergoeconomic analysis of an Ethylene process. J Sci Eng 2001;4(2):94–104.
[15] Balli O, Aras H, Hepbasli A. Exergoeconomic analysis of a combined heat and power (CHP) system. Int J Energy Res 2008;32(4):273–89.
[16] Silvera JL, Tuna CE. Thermoeconomic analysis method for optimization of combined heat and power systems Part 1. Prog Energy Combust Sci 2003;29:479–85.
[17] Bejan A, Tsatsaronis G, Moran M. Thermal design & optimization. New York: John Wiley & Sons, Inc.; 1996.
[18] Xiang JY, Cali M, Santarelli M. Calculation for physical and chemical exergy of flows in systems elaborating mixed-phase flows and a case study in an IRSOFC plant. Int J Energy Res 2004;28:101–15.
[19] Wepfer WJ, Gaggioli RA, Obert EF. Proper evaluation of available energy for HVAC. ASHRAE Trans 1979;85(1):214–30.
[20] Kotas TJ. The exergy method of thermal power plants. Malabar, Florida: Krieger Publishing Company; 1995.
[21] Coskun C, Oktay Z, Dincer I. New energy and exergy parameters for geothermal district heating systems. Appl Therm Eng 2009;29(11–12):2235–42.
[22] Van Gool W. Energy policy: fairly tales and factualities. In: Soares ODD, Martins da Cruz A, Costa Pereira G, Soares IMRT, Reis AJPS, editors. Innovation and technology-strategies and policies. Dordrecht: Kluwer; 1997. p. 93–105.
[23] Tsatsaronis G, Winhold M. Exergoeconomic analysis and evaluation of energy conversion plants Parts 1 & 2. Energy 1985;10:69–94.
[24] Sciubba E. Beyond thermoeconomics ? The concept of extended exergy accounting and its applications to the analysis and design of thermal systems. Exergy Int J 2001;1:68–84.
[25] Rosen MA, Dincer I. Exergoeconomic analysis of power plants operating on various fuels. Appl Therm Eng 2003;23:643–58.
[26] Ozgener O, Hepbasli A. Exergoeconomic analysis of a solar assisted ground-source heat pump greenhouse heating system. Appl Therm Eng 2005;25:1459–71.
[27] Utlu Z, Hepbasli A. Exergoeconomic aspects of sectoral energy utilization for Turkish industrial sector and their impact on energy policy. Energy Policy 2009;37:577–87.
[28] Rosen MA, Scott DS. The enhancement of a process simulator for complete energy-exergy analysis. In: Gaggioli MRA, editor. Analysis and design of advanced energy systems: fundamentals, 3–1. New York: American Society of Mechanical Engineers; 1985. p. 71–80.
[29] Rosen MA, Dincer I. Thermoeconomic analysis of power plants: an application to a coal-red electrical generating station. Energ Convers Manage 2003;44:1633–51.
[30] Sahin AD, Dincer I, Rosen MA. New spatio-temporal wind exergy maps. Trans ASME J Energy Resour Technol 2006;128(3):194–202.
[31] Ozgener O, Ozgener L, Dincer I. Analysis of some exergoeconomic parameters of small wind turbine system. Int J Green Energy 2009;6(1):42–56.
[32] Weston A, Hermann. Quantifying global exergy resources. Energy 2006;31(12):1685–702.
[33] Pope K, Dincer I, Naterer GF. Energy and exergy efficiency comparison of horizontal and vertical axis wind turbines. Renew Energy 2010;35:2102–13.
[34] Sahin AD, Dincer I, Rosen MA. Thermodynamic analysis of wind energy. Int J Energy Res 2006;30(8):553–66.
[35] Dincer I, Rosen MA. Thermodynamic aspects of renewables and sustainable development. Renew Sustain Energy Rev 2005;9:169–89.
[36] Xydis G, Koroneos C, Loizidou M. Exergy analysis in a wind speed prognostic model as a wind farm sitting selection tool: a case study in Southern Greece. Appl Energy 2009;86:2411–20.
[37] Koroneos C, Katopodi E. Maximization of wind energy penetration with the use of H_2 production—an exergy approach. Renew Sustain Energy Rev 2011;15:648–56.
[38] Koroneos C, Spachos T, Moussiopoulos N. Exergy analysis of renewable energy sources. Renew Energy 2003;28:295–310.
[39] Ozgener O, Ozgener L. Exergy and reliability analysis of wind turbine systems: a case study. Renew Sustain Energy Rev 2007;11:1811–26.
[40] Ahmadi A, Ehyaei MA. Exergy analysis of a wind turbine. Int J Exergy 2009;6(4):457–76.
[41] Baskut O, Ozgener O, Ozgener L. Effects of meteorological variables on exergetic efficiency of wind turbine power plants. Renew Sustain Energy Rev. doi:10.1016/j.rser.2010.06.002.
[42] Romero-Terneroa V, García-Rodrígueza L, Gómez-Camachob C. Thermoeconomic analysis of wind powered seawater reverse osmosis desalination in the Canary Islands. Desalination 2005;186:291–8.
[43] Balta MT, Dincer I, Hepbasli A. Performance and sustainability assessment of energy options for building HVAC applications. Energy Build 2010;42: 1320–8.
[44] International Energy Agency (IEA). Oil Crises and Climate Challenges: 30 Years of Energy Use in IEA Countries. International Energy Agency, Paris, http://iea.org/textbase/nppdf/free/2004/30years.pdf [retrieved May 15, 2009].
[45] Schmidt D, Juusela MA. Low-exergy systems for heating and cooling of buildings. In: Proceedings of the 21st conference on passive and low energy architecture. 2004.
[46] International Energy Agency (IEA). Low exergy heating and cooling of buildings–Annex 37, http://www.vtt.fi/rte/projects/annex37/Index.htm [retrieved May 19, 2008].
[47] Balta MT, Kalıncı Y, Hepbasli A. Evaluating a low exergy heating system from the power plant through the heat pump to the building envelope. Energy Build 2008;40(10):1799–804.
[48] Sakulpipatsin P, Itard LCM, van der Kooi HJ, Boelman EC, Luscuere PG. An exergy application for analysis of buildings and HVAC systems. Energy Build 2010;42:90–9.
[49] Kalinci Y, Balta MT, Hepbasli A. Performance assessment of a geothermally heated building. Energy Policy 2009;37(4):1502–8.
[50] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. Canada: John Wiley & Sons, Inc; 1996.
[51] Petrakopoulou F, Boyano A, Cabrera M, Tsatsaronis G. Exergoeconomic and exergoenvironmental analyses of a combined cycle power plant with

chemical looping technology.International J Greenhouse Gas Control (2010), doi:10.1016/j.ijggc.2010.06.008.

[52] Tsatsaronis G, Morosuk T. Advanced exergetic analysis of a novel system for generating electricity and vaporizing liquefied natural gas. Energy 2010;35(2):820–9.

[53] Lazzaretto A, Tsatsaronis G. SPEC.O. A systematic and general methodology for calculating efficiencies and costs in thermal systems. Energy 2006;31: 1257–89.

[54] Kalinci Y, Hepbasli A, Dincer I. Exergoeconomic analysis of hydrogen production from plasma gasification of sewage sludge using specific exergy cost method. Int J Hydrogen Energy (2011), doi:10.1016/j.ijhydene.2010.11.124.

[55] Wind Energy Resource Atlas of the United States. http://rredc.nrel.gov/wind/pubs/atlas/ [Access date: 8 December 2010].

[56] Wind Energy as a Siting Criteria for Potential Wind Parks. Appendix 3A. DRAFT EIS/EIR/DRI.

[57] Lee KC. Classification of geothermal resources by exergy. Geothermics 2001;30:431–42.

[58] Raman V, Tiwari GN, Pandey HD. Life cycle cost analysis of a hybrid photovoltaic-thermal water and air collector: a comparison study based on energy and exergy. Int J Low Carbon Technol 2008;3(3): 173–90.

[59] Fiaschi D, Lombardi L. Integrated gasifier combined cycle power plant with integrated CO_2-H_2S removal: performance analysis, life cycle assessment and exergetic life cycle assessment. Int J Appl Thermodyn (IJAT) 2002;5(1): 13–24.